Non - Metallic Materials
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Module – 04
Mechanical properties of non – metallic and composite materials
Lecture – 21
Composite materials: Particle – reinforced composites, and fiber reinforced composites

Welcome to my course Non-Metallic Materials. And this is module number 4, Mechanical properties of non-metallic and composite materials. And we are in lecture number 21, Composite materials, Particle - reinforced composite, and fiber reinforced composite.

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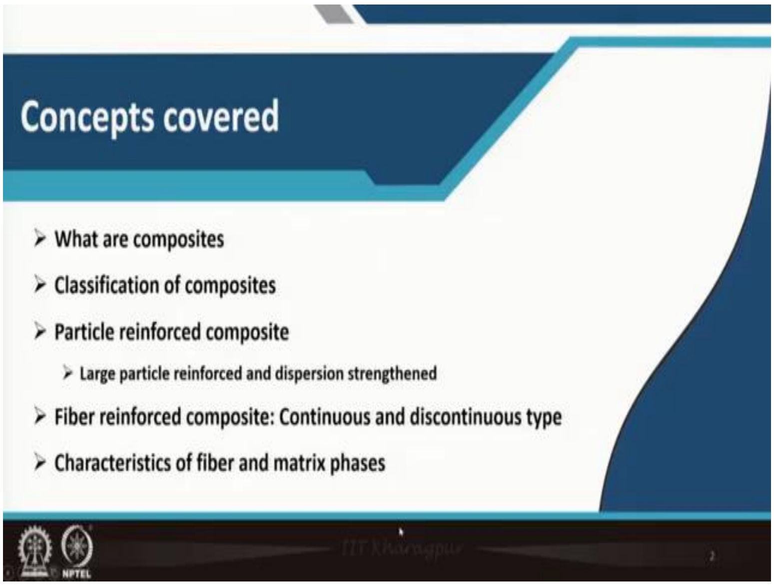

So, in this particular lecture, we will define what is exactly a composite, then we will classify the composites, and particle reinforce composite this is large particle reinforced composite, and also we will talk about dispersion strengthened composite where crack shielding is one of the major mechanism for its large strength.

And then we will introduce fiber reinforced composite, both continuous as well as discontinuous type of fibers which are experience a longitudinal as well as transverse kind of loading will be analyzed, and characteristics of the fiber phase and the matrix phase will be introduced.

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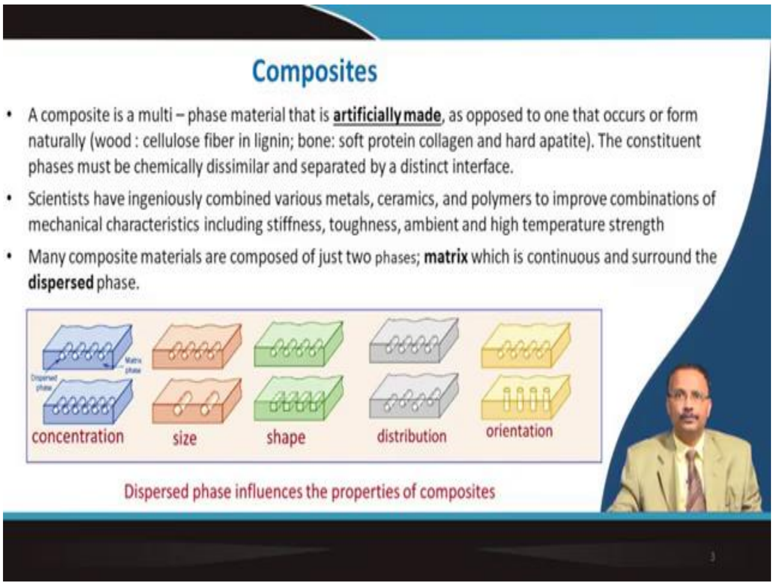

Now, this composite first it should be a multi phase material and this is artificially made. So, this is not natural. So, natural composite for example, wood is there where cellulose fiber is in is a reinforcing kind of thing in the softer lignin matrix or bone is also a natural composite soft protein collagen and hard apatite they forms the composite. So, here we will be talking only about artificial manmade composite, and the constituents phases must be chemically dissimilar and separated by a very distinct interface region.

So, people have made it in the laboratory using various metals, ceramics, and polymers to improve the combinations of mechanical characteristics which includes the stiffness of the composite, toughness and both ambient as well as high temperature strength.

Most of the composites they are having two phases one is matrix usually they are continuous and it surrounds the dispersed phase. And dispersed phase they are strong elastic material. So, depending on the types of composite there are various types of ah dispersed phase that influence the properties of the composite.

The first important parameter is the concentration of this dispersed phase, the second one is their size relative size, third one is the shape as you can see, fourth one is distribution, here it is a linear type of distribution, here it is somewhat corrugated type of distribution. And also the orientation of the dispersed phase, in one case it is parallel oriented, another one it is longitudinally oriented.

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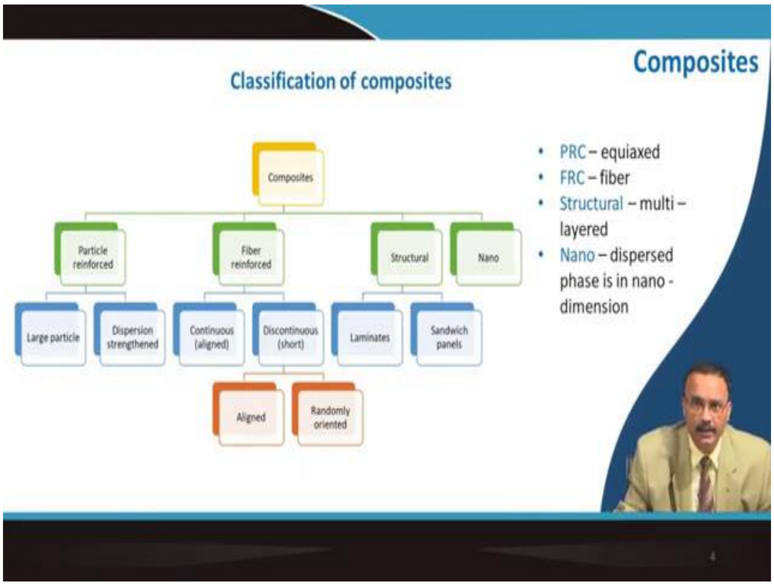

So, based on that we can classify the composites. And in today's lecture, we will be only talking about particle reinforced composite and fiber reinforced composite. In the next lecture, I will take structural and nano composites separately.

So, particle reinforced composite you can have large particle or relatively smaller particle which we call dispersion strengthened composite. Fiber reinforced usually they are continuous fiber which are aligned or it could be discontinuous fiber which is short, shorter in length as compared to the long fiber reinforcement. Now, this discontinuous fiber they could be either aligned or they could be totally random.

As far as the structural composite it considered mostly it is laminate type or sandwich panel in the next lecture we will be talking about it, and we will talk about the nano composite. So, this particle reinforced composite abbreviated as PRC, usually equiaxed particles are considered.

Fiber reinforced composite it is fiber they are the reinforcing agent. And structural composite they are multi-layered and in case of nano composite, their dispersed phase is in nano dimension. So, dispersion is in the nano dimension.

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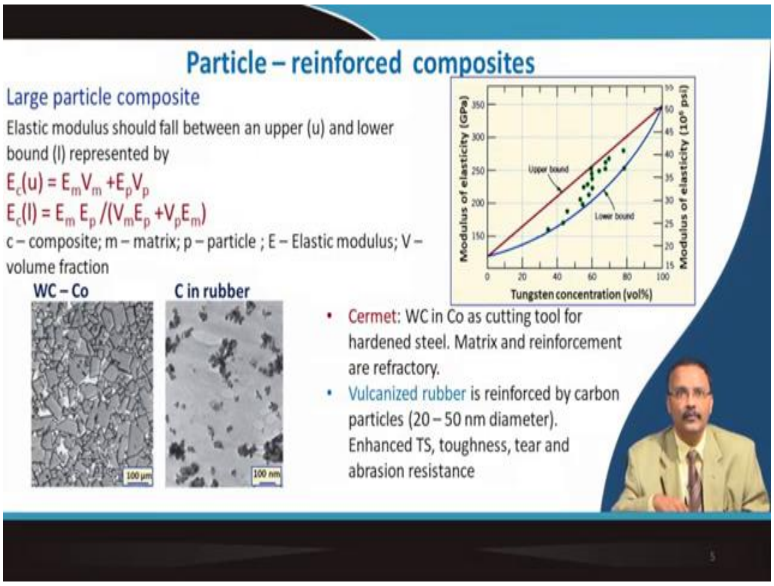

So, first let us look into this particle reinforced composite. So, it is having large particle as a reinforcing agent. And you can have two limit of the elastic modulus; the first one is the upper limit where it follows the rule of mixture. So, c stands for composite, m stands for matrix, and p stands for particle, E is the elastic modulus here and V is the volume fraction of the particles.

So, it is following a rule of mixture and there is a lower limit, this I have derived later part in this particular lecture. So, in the lower limit this equation is valid. So, for the tungsten carbide which is the reinforcing ceramic phase, it forms a composite with a metal cobalt.

So, as you can understand if there is any crack propagation then cobalt will start to plastically deform and the crack energy will be taken away from the propagating crack. And tungsten carbide is a very hard material. So, tungsten carbide and cobalt that is being used as a cutting tool for the hardened steel very hard steel can be cut with this kind of composite. So, the matrix is a metal which is ductile and the reinforcement is a refractory ceramic material.

Another example one can give is vulcanized rubber, which is reinforced. This vulcanized rubber you know about it, I talked about it in one of my lectures. It is reinforced by carbon particles they are having very small size 20 to 50 nanometer diameter.

So, the length scale wise you see tungsten carbide which is this dark region and cobalt is this lighter region you see very large particles are dispersed in a continuous matrix, but here the carbon is a very small as compared to your vulcanized rubber matrix. So, this kind of thing is used in rubber industry, it increases the tensile strength, toughness, tear and abrasion resistance of the tire.

So, usually all the values of the modulus of this composite depending on the percentage of this concentration of your reinforcing phase, it will be within this upper and lower limit as just I have defined.

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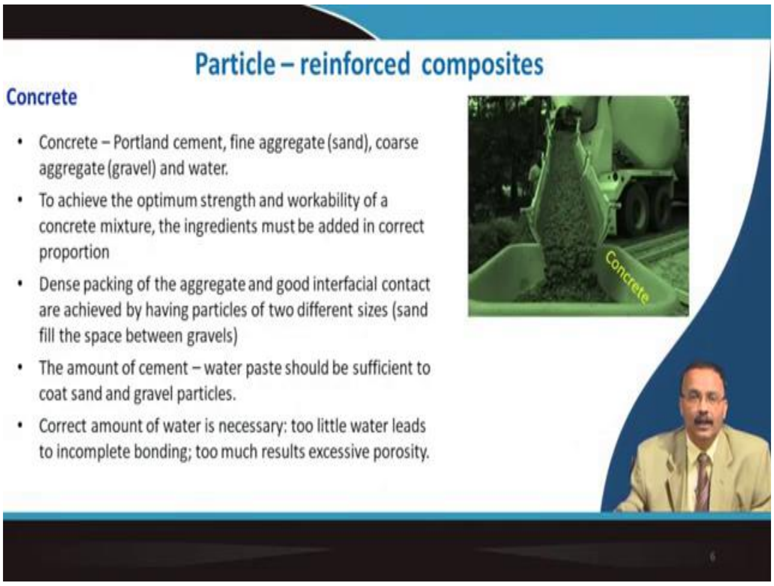

So, concrete is another particle reinforced composite which all of you are familiar with. It is basically Portland cement, fine aggregate which is sand and coarse aggregate gravel the stone chips and water that is mixed together to form this kind of composite. It sets ah within a very short time depending on its final setting time. It starts with initial setting time and then it finally, sets.

To achieve the optimum strength and workability of the concrete mixture, the ingredient must be added in correct proportion. So, in order to get a particular strength you will have to have a certain proportion maintained between the cement phase, the finer aggregate, and coarser aggregate different ratios are available along with the water.

Dense packing of the aggregate and good interfacial contact is achieved by having particles of two different size. So, your stone chip particles that void space is filled up with sand and the void space of the sand is filled up with the cementitious phase to have a relatively larger packing efficiency. And on top of that you have a ramming done, so that it they are properly packed.

Amount of cement and water ratio is very important. So, that should be sufficient to coat the cementitious material on top of this fine and coarse aggregate. And correct amount of water is necessary, very small amount of water they will lead to incomplete bonding and too much of water if you add then it will actually lead to the porosity in the set cement.

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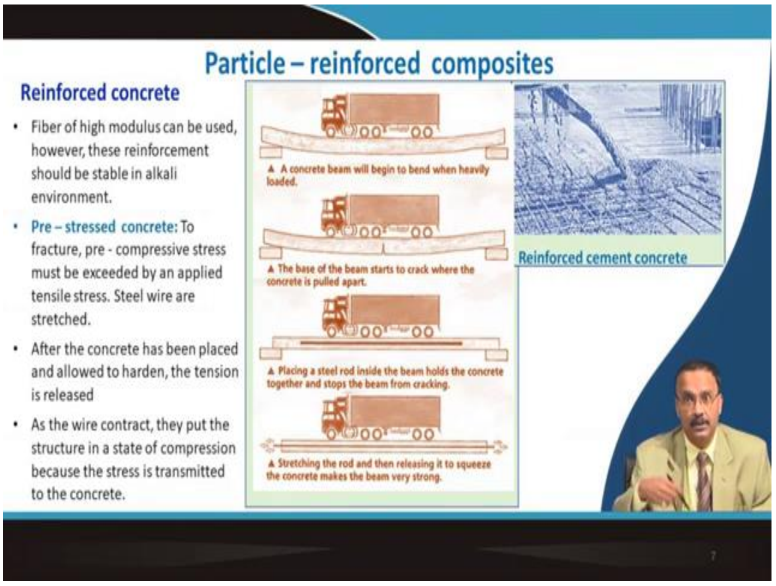

So, normal cementitious concrete material they cannot withstand the bending load as you can see; when the load is pretty heavy then the surface is under tension, the outer surface, so crack will propagate. So, in order to remove, you need to have reinforcement in terms of the steel rod as you can see the steel rod is there which acts as a metal reinforcement in a otherwise compressive strong 70 shears matrix.

So, this will allow to carry the load and if you want to make it still stronger then you put a this steel tendon and apply a tensile load while you put this concrete material and allow it to set. So, this is known as pre-stress concrete.

And it actually generates a compressive stress field the same like we defined in case of transformation toughening in case of glass tempered glass strengthening, something similar it occurs here also. And this leads to a stress of compression because the stress is transmitted to the concrete and it gives a very very high strength structure.

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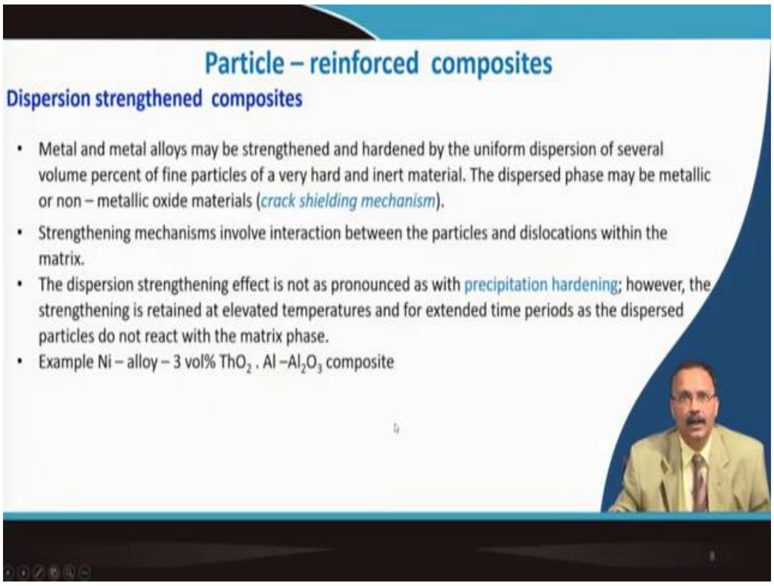

Dispersion strength and composite they are something similar to the precipitation hardened material. So, there is a difference because in the precipitation hardened material at high temperature if you go, then the precipitates can dissolve back. But here in case of dispersion strengthening they are still there in the matrix and basically the crack is shielded by this hard inclusion.

So, the strengthening mechanism that involve interaction between the particles and dislocation within the matrix. The dispersion strengthening effect as I said is not as pronounced at precipitation hardening, but the strengthening is retained at elevated temperature for extended period of time, in case of precipitation hardening, for the metallic material, many time the precipitates dissolve back into the matrix.

So, example is nickel alloy, metallic alloy, 3 volume percent thorium oxide or aluminum oxide in aluminum matrix, they are the example of the particle strengthened case in case of this dispersion kind of strengthening.

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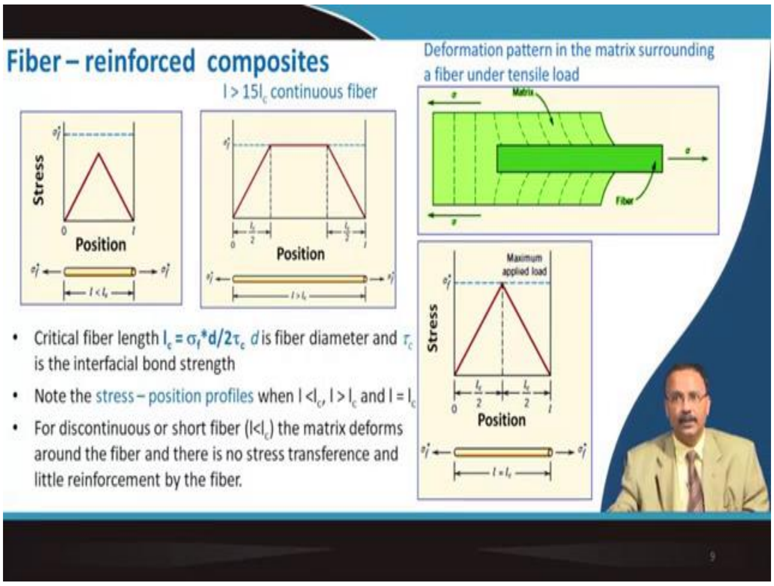

So, now we will talk about the fiber reinforcement where the fiber is a reinforcing agent and you have the matrix which is softer. So, when you try to pull the fiber then this stress field as you can see we will have to overcome this stress field and it depends on how strongly the fiber is bonded into the matrix. So, the deformation pattern you can see here that when you try to take out the fiber in terms of the fiber pull out from the matrix then you will have to spend energy.

So, the length of the fiber is very important and we can define a critical length of the fiber which is related to the stress that you are applying, the tensile load and the area that will define the stress. And this stress ah is important and the diameter of the fiber is important, and the value tau c which is the interfacial bond strength which I was talking about that is important. So, you can define what is the critical length of the fiber that is required for the strengthening.

So, as you can see if your fiber length is less than this critical length then the maximum load actually is not achieved, is not being taken by the fiber for the reinforcement. On the other hand, if you have a larger fiber then most of the load that is taken by the fiber which is about 15 times larger than the critical length, so this is achievable, and this is actually practically adaptive to use this kind of fiber. And if it is right the critical length then you can see only at the midpoint you have the maximum load that is being carried.

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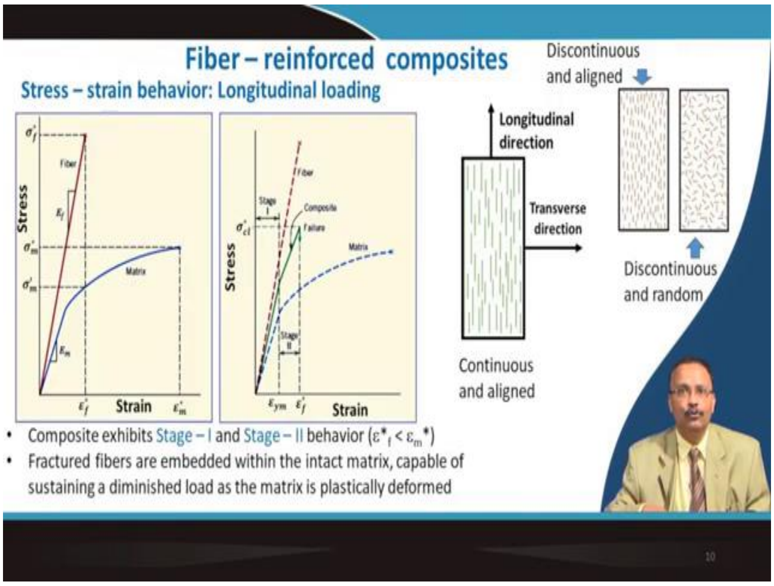

So, we will go for the continuous fiber which are aligned as you can see and we are applying here a longitudinal direction we are applying the stress. So, we can apply the stress in transverse reduction as well, but this I will show that this is much more effective as far as the strength of the composite is concerned.

Now, if you look at the individual fiber as well as the matrix which is many case, the polymeric material, fiber could be ceramic material, carbon, glass and this could be resin. So, more or less the this matrix they have this kind of ductile behavior and the fiber is elastic behavior.

And the fiber usually have higher tensile modulus as compared to the matrix, but the matrix gives you much larger strain as compared to the fiber. So, the composite is in between. So, you can identify there are two stage, the first stage and second stage behavior, the second stage here is actually taken by this strain effect of the matrix.

So, when the fiber is fractured at this stress then the failure should occur should occur in the composite, but fractured fibers they are embedded within an intact almost intact matrix because your matrix is not fractured at that particular stress. So, they are capable of sustaining a diminished load as the as the matrix is plastically deformed. So, that is the root cause of the reinforcement.

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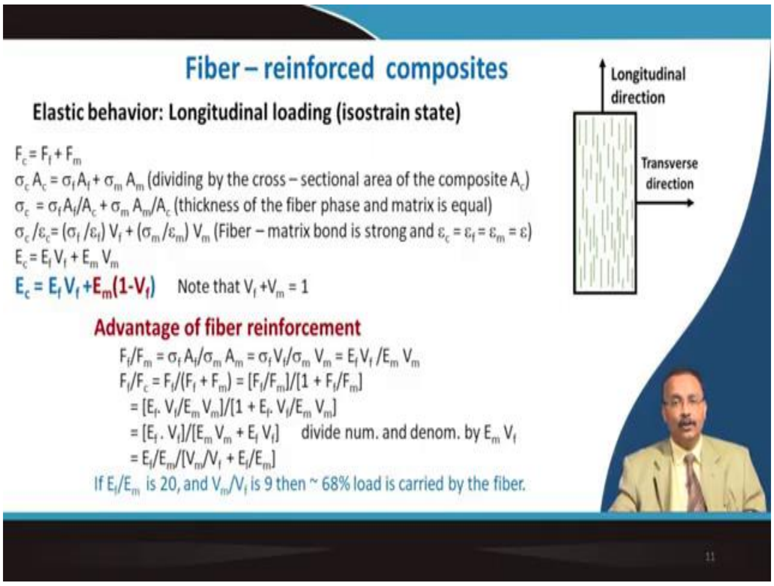

Now, we can ah just derive the usefulness of this kind of reinforcement and here in this case as you can see that you are applying a load here, and basically the strain of the fiber of the composite and the matrix phase they are all equal, but the stress is not equal. So, we will show that the applied stress is being transformed mostly to the fiber and therefore, the reinforcement is taking place because the fiber is much stronger as compared to the matrix

So, if you see the force that is there in the composite here also c is composite F fiber m is the matrix then you can see F c is equal to F f plus F m. Now, I have done this small mathematical calculation, so you can always think the force in terms of stress and the corresponding area of the composite.

And then finally, you get this relation for the composite stress, and since the thickness of this phase the thickness is same for your fiber and the matrix because it is throughout your composite, so you can replace it by volume fraction.

And as I said the strain will remain constant, so this 3 things are equal to epsilon. So, that basically gives you the rule of mixture E c is equal to E f V f plus E m V m. And this volume at volume of the fiber phase you can replace V m by 1 by V f because this two phase volumetric phase is actually unity.

We can also calculate the force that is taken by the fiber as compared to the composite by this simple mathematics. So, I am not going into the line by line details you can work it out and finally, you come up with this relation where the force on the fiber divided by force of the composite that is related with the modulus of the fiber and modulus of the matrix along with their volume fraction.

So, this relation is important because here if you take the fiber is to matrix is 20 times larger because usually the fiber is having larger elastic modulus and the volume fraction of the fiber is about 10 percent, so that leads to V m by V F is 9, then almost 68 percent of the applied load that actually is carried out by the fiber. And since, the fiber is strong your composite is having much larger strength.

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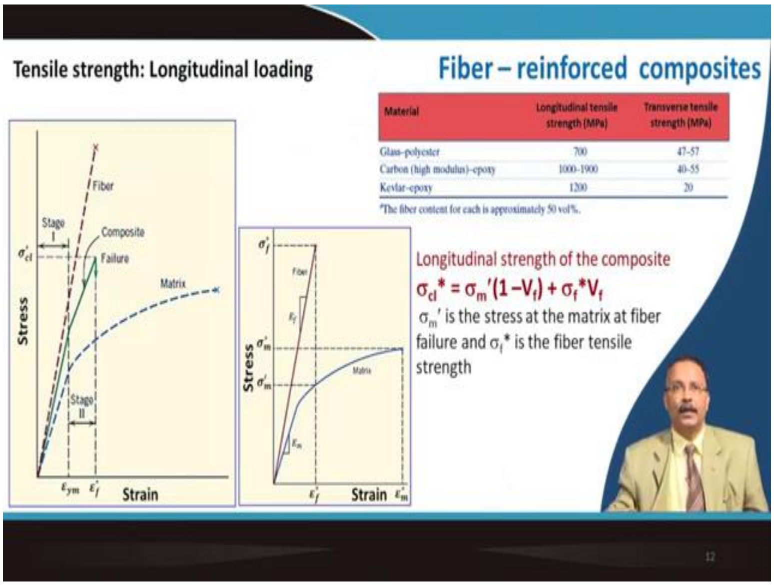

So, if I can calculate the tensile strength in case of longitudinal loading, so that is defined by this. So, this is the composite tensile stress in case of longitudinal loading. And that relates with of course, the sigma F V F will be there, but here as you can see that when this one actually fails then you have at the failure stress you have the sigma m is here, I mean this does not fail because of the ductile nature of this matrix.

So, you can replace this one and you can get the longitudinal tensile strength calculated of this kind of matrix. So, you can see the longitudinal tensile strength for glass polyester carbon epoxy they are quite large, but when it is in the transverse direction once you are applying the stress at the transverse direction.

So, fiber is oriented in z direction you are apply the stress like here then it is miserably small values, the value of the transverse tensile strength is too less as compared to your longitudinal case.

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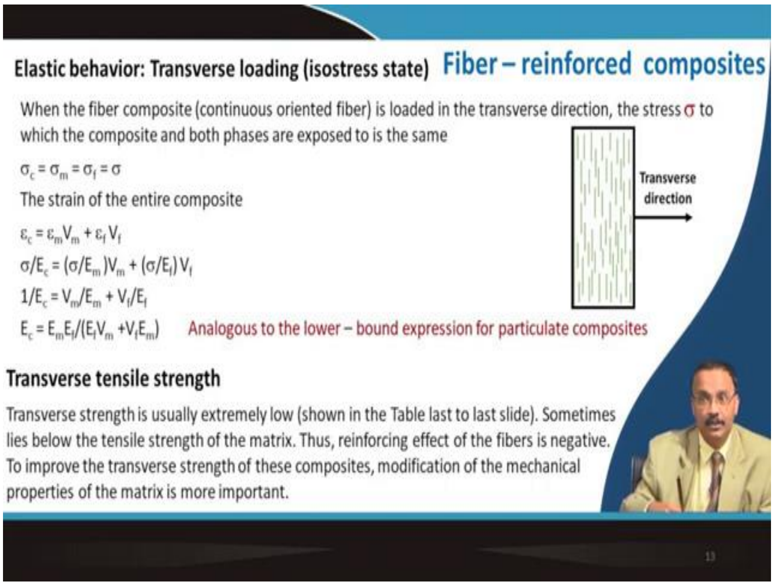

So, transverse loading, I can also work it out. And here actually as you can see that the stress here is same. In the last class strain, it was the iso-strain condition, but here stress is same because you are applying a tensile direction, so it is exposed area is similar. And here we can do this is the strain value is given by this relation I replace it by the elastic modulus, and then I come up with a relation of the composite elastic modulus with the volume fraction of matrix and volume fraction of fiber.

And this relation if you remember correctly was the lower limit which I described in my couple of slides back in case of particulate composite. So, we define a upper limit and lower limit. The upper limit is defined by the rule of mixture and the lower limit is defined by this relation.

So, as I have said transverse tensile strength are miserably small, so your fiber effect is not reinforcement. But actually it is adding a negative influence and in fact, the strength is less than the matrix 7, so usually we do not do that.

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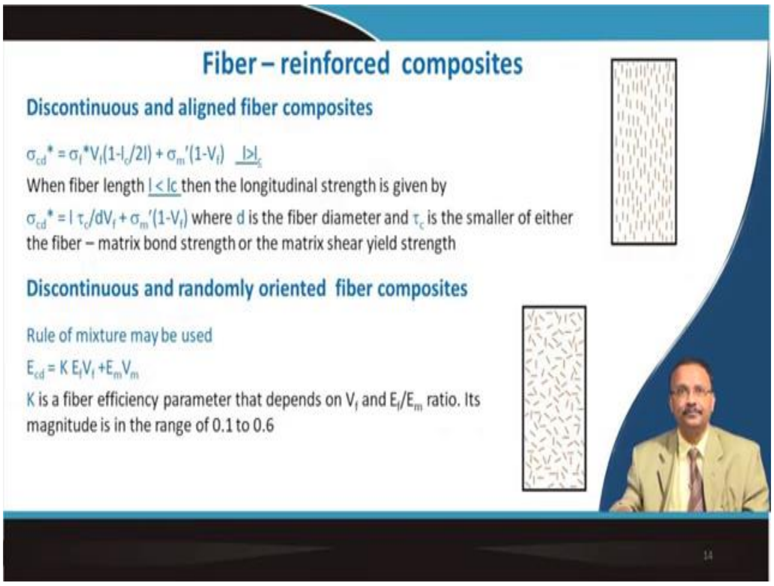

Now, in case of discontinuous and aligned fiber composite for this one, this relations are all empirical, but it is something related to the one that we have derived. For example, when the length of the fiber is more than the critical length then this relation is valid. And when the length is less than the critical length then this relation is valid. So, for discontinuous and randomly oriented fiber like this this is more or less rule of mixture, but an additional term K is involved here.

So, this is a fiber efficiency parameter and that basically depends on the volume fraction of the fiber and the ratio of fiber elastic modulus and the elastic modulus of the matrix. And usually its magnitude is in the range of 0.1 to 0.6.

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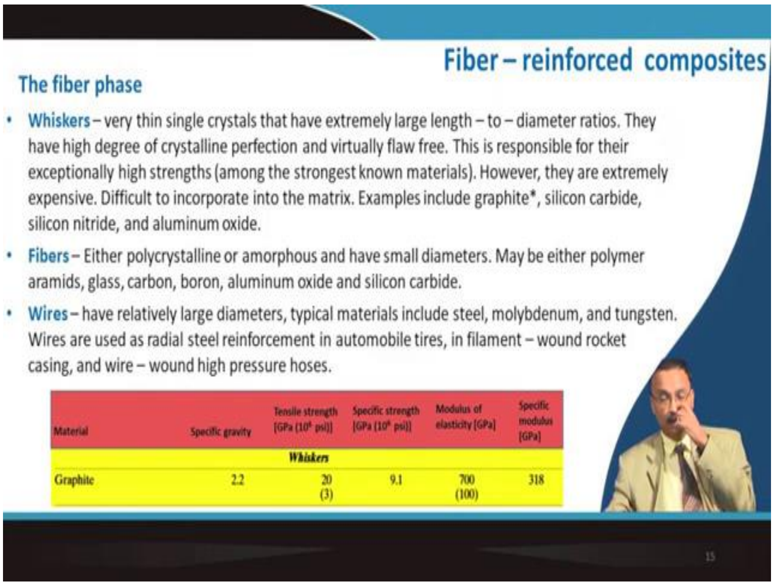

The fiber phase usually 3 types of fiber phases are used. First one is a whisker is a very thin single crystalline material, but they are very very expensive and very large length to diameter ratio. Of course, they have very high degree of crystalline perfection and they are virtually free of any defect. So, this is the ideal thing that one can use, but it is too expensive. So, in practical purpose whiskers are not used.

So, examples of whisker are available in case of graphite, silicon carbide, silicon nitride and aluminum oxide fibers a defect free whiskers. Usually the fibers are used either in polycrystalline form or amorphous form they have usually small diameter it could be polymeric material like aramids are there, glass, ceramic fibers are there, boron and aluminum oxide and silicon carbide they are the normal fiber phase that is being used.

Or one can use wire, which are having relatively larger diameter as compared to the fibers and this is particularly useful for the reinforcement of the cementitious material and it includes steel, steel fibers are used in concrete, steel wires in fact. Molybdenum and tungsten they are expensive that those wires are also used.

For example, in the reinforcement of the automobile tire we use the wires or the filament wound rocket casing that is also common. Wire wound high pressure hoses for petroleum, petrol and water we use this kind of reinforcement.

So, typical example of the so called whiskers graphite is one of them, specific gravity is around 2.2 not that heavy, tensile strength for the whiskers you can see it is about 20 GigaPascal.

Specific strength is quite large because your specific gravity is small. Modulus of elasticity is tremendous high 700 GPa, and specific modulus of course, it will be high because the specific gravity is low. So, whiskers are extremely important for specialty composite, but as I said that they are very expensive. So, fiber and wire reinforcements are usually used for a practical purpose.

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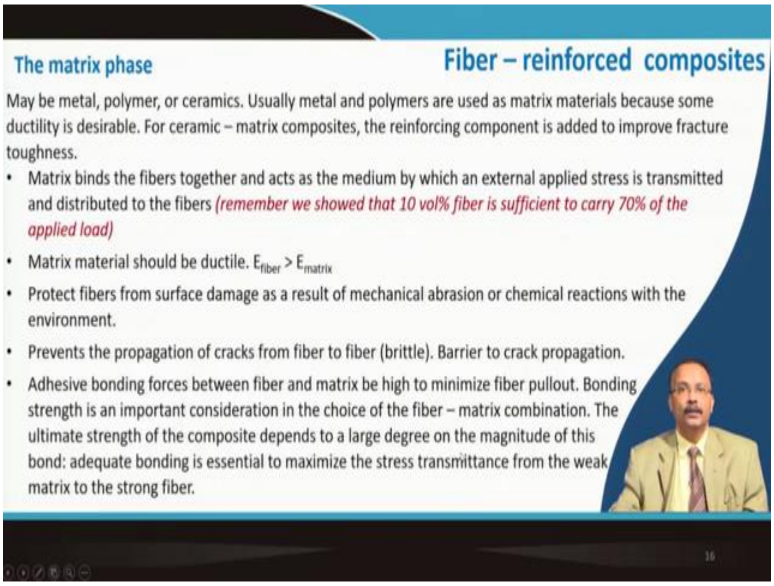

The matrix phase that could be metal that could be polymer or ceramics usually metal and polymers are used in the matrix material because they have some kind of ductility. So, when the crack propagates the energy is transformed into the ductile matrix and the energy spent for plastic deformation along with the slip plane.

So, ceramic matrix composite, the reinforcement component is added to improve the fracture toughness. That already I have defined that crack bridging mechanism is one of them and for dispersion strengthening crack shielding mechanism is also applicable.

So, matrix binds the fibers together and acts as a medium by which an external applied stress when you are applying on the composite they are distributed to the fibers. So, in couple of lectures back, we have calculated that 10 volume percent fiber if you use and when the along when the orientation is longitudinal then about 70 percent of the load that is being carried by the stronger fiber as compared to the softer matrix.

So, matrix material should be ductile, but the slope of the stress strain curve, the fiber should have larger elastic module as compared to the matrix. And this should protect the fiber surface fiber from the surface damage for mechanical abrasion or chemical reaction or whatever. So, you know that little bit of small crack if you introduce in the matrix in the fiber surface then it can have a catastrophic effect because after all they are brittle in nature.

Prevents the propagation of the crack the matrix prevent the propagation of the crack from fiber to fiber. So, in between the matrix is there. So, the crack cannot propagate. So, it acts as a barrier of this crack propagation. And adhesive bonding between the fiber and matrix must be higher to minimize the fiber pull out. So, they should have strong adhesion between the fiber and the matrix, so that while you are loading it then fiber pull out does not take place at lower load level.

So, bonding strength is important consideration of the choice of the fiber and matrix combination. The ultimate strength of the composite that depends on a large extent to the magnitude of this bond the interfacial bond, and adequate bonding is essential to maximize the stress transmittance from the weaker matrix zone to stronger fiber zone.

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So, the reference for this part of the lecture is from the book by W. D. Callister, and this pages 564 to 583 that can be used as a study material. And apart from that, there are 3 good reference book that you can consider, and for further reading, and solving the assignment problems given there.

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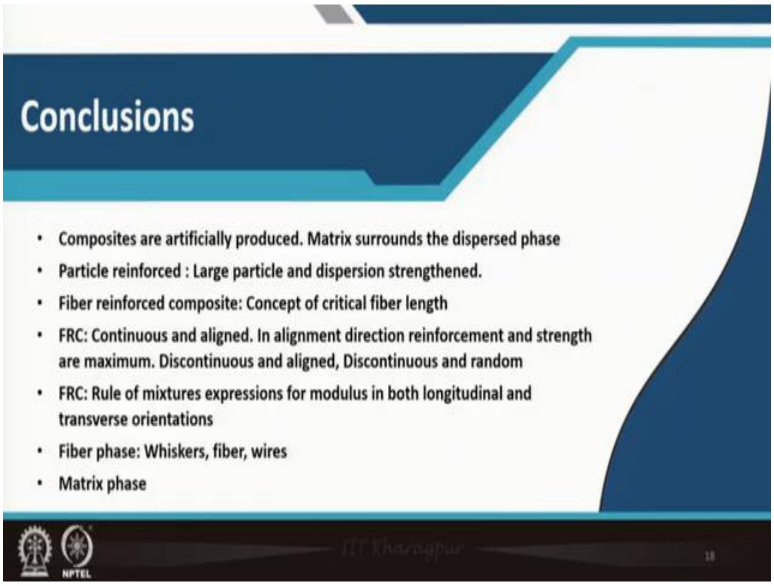

So, we have explained that the composites are artificially produced, and matrix surrounds the dispersed phase. Particle reinforcement, large particle and dispersion strengthened are the two different types of composite. Fiber reinforced composite we have defined the critical fiber length concept and how the load is transmitted there.

Fiber reinforced composite, they are either continuous or aligned. So, in the alignment direction reinforcement and strength are maximum in the longitudinal direction. Discontinuous and aligned that also was described and the empirical relation was shown about their strength. And discontinuous and random case was also elucidated.

For fiber reinforced composite rule of mixture expression, for modulus in both longitudinal and transverse direction that was derived. And fiber phase usually there are 3 different types one is whisker, fiber, and wires. And then finally, we talked about the characteristics of the matrix phase. In the next class, we will be taking particulate laminated composite and the nano composite.

Thank you for your attention.